

¹ Fitness tracking reveals task-specific associations
² between memory, mental health, and exercise

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⁸ **Abstract**

⁹ Physical exercise can benefit both physical and mental well-being. Different forms of exercise
¹⁰ (i.e., aerobic versus anaerobic; running versus walking versus swimming versus yoga; high-
¹¹ intensity interval training versus endurance workouts; etc.) impact physical fitness in different
¹² ways. For example, running may substantially impact leg and heart strength but only moderately
¹³ impact arm strength. We hypothesized that the mental benefits of exercise might be similarly
¹⁴ differentiated. We focused specifically on how different forms of exercise might relate to different
¹⁵ aspects of memory and mental health. To test our hypothesis, we collected nearly a century's
¹⁶ worth of fitness data (in aggregate). We then asked participants to fill out surveys asking them
¹⁷ to self-report on different aspects of their mental health. We also asked participants to engage in
¹⁸ a battery of memory tasks that tested their short and long term episodic, semantic, and spatial
¹⁹ memory. We found that participants with similar exercise habits and fitness profiles tended to
²⁰ also exhibit similar mental health and task performance profiles.

²¹ **Introduction**

²² Engaging in physical activity (exercise) can improve our physical fitness by increasing muscle
²³ strength (Crane et al., 2013; Knuttgen, 2007; Lindh, 1979; Rogers and Evans, 1993), increasing bone
²⁴ density (Bassey and Ramsdale, 1994; Chilibeck et al., 2012; Layne and Nelson, 1999), increasing
²⁵ cardiovascular performance (Maiorana et al., 2000; Pollock et al., 2000), increasing lung capac-
²⁶ ity (Lazovic-Popovic et al., 2016) (although see Roman et al., 2016), increasing endurance (Wilmore
²⁷ and Knuttgen, 2003), and more. Exercise can also improve mental health (Basso and Suzuki, 2017;
²⁸ Callaghan, 2004; Deslandes et al., 2009; Mikkelsen et al., 2017; Paluska and Schwenk, 2000; Raglin,
²⁹ 1990; Taylor et al., 1985) and cognitive performance (Basso and Suzuki, 2017; Brisswalter et al.,
³⁰ 2002; Chang et al., 2012; Ettnier et al., 2006).

³¹ The physical benefits of exercise can be explained by stress-responses of the affected body tis-
³² sues. For example, skeletal muscles that are taxed during exercise exhibit stress responses (Morton
³³ et al., 2009) that can in turn affect their growth or atrophy (Schiaffino et al., 2013). By comparison,
³⁴ the benefits of exercise on mental health are less direct. For example, one hypothesis is that ex-
³⁵ ercise leads to specific physiological changes, such as increased aminergic synaptic transmission
³⁶ and endorphin release, which in turn act on neurotransmitters in the brain (Paluska and Schwenk,
³⁷ 2000).

³⁸ Speculatively, if different exercise regimens lead to different neurophysiological responses, one
³⁹ might be able to map out a spectrum of signalling and transduction pathways that are impacted
⁴⁰ by a given type, duration, and intensity of exercise in each brain region. For example, prior work
⁴¹ has shown that exercise increases acetylcholine levels, starting in the vicinity of the exercised
⁴² muscles (Shoemaker et al., 1997). Acetylcholine is thought to play an important role in memory
⁴³ formation (Palacios-Filardo et al., 2021, e.g., by modulating specific synaptic inputs from entorhinal
⁴⁴ cortex to the hippocampus, albeit in rodents). Given the central role of these medial temporal
⁴⁵ lobe structures play in memory, changes in acetylcholine might lead to specific changes in memory
⁴⁶ formation and retrieval.

⁴⁷ In the present study, we hypothesize that (a) different exercise regimens will have different,

48 quantifiable impacts on cognitive performance and mental health, and that (b) these impacts will
49 be consistant across individuals. To this end, we collected a year of fitness tracking data from
50 each of 113 participants. We then asked each participant to fill out a brief survey in which they
51 self-evaluated several aspects of their mental health. Finally, we ran each participant through a
52 battery of memory tasks, which we used to evaluate their memory performance along several
53 dimensions. We examined the data for potential associations between memory, mental health, and
54 exercise.

55 Results

- 56 • exploratory analysis (correlations)
 - 57 – Memory-memory
 - 58 – fitness-fitness
 - 59 – survey-survey
 - 60 – (fitness + survey)-memory
- 61 • predictive analysis (regressions)
 - 62 – Predict memory performance on held-out task from other tasks
 - 63 – Predict memory performance on each task using fitness data
 - 64 – Predict memory performance on each task using survey data
- 65 • Reverse correlations: look at recent changes versus baseline trends
 - 66 – Fitness profile that predicts performance on each task (barplots + timelines)
 - 67 – Fitness profile for each survey demographic (barplots + timelines)
 - 68 * Select out mental health demographics (based on meds, stress levels)

69 **Discussion**

- 70 • summarize key findings
- 71 • correlation versus causation
- 72 • what can vs. can't we know? we can identify correlations, but not causal direction– e.g. we
73 cannot know whether exercise *causes* mental changes versus whether people with particular
74 neural profiles might tend to engage in particular exercise behaviors. that being said, we *can*
75 separate out baseline tendencies (e.g., how people tend to exercise in general) versus recent
76 changes (e.g., how they happened to have exercised prior to the experiment).
- 77 • related work (exercise/memory, exercise/mental health), what this study adds
- 78 • future direction: towards customized physical exercise recommendation engine for optimiz-
79 ing mental health and mental fitness

80 **Methods**

81 We ran an online experiment using the Amazon Mechanical Turk platform. We collected data
82 about each participant's fitness and exercise habits, a variety of self-reported measures concerning
83 their mental health, and about their performance on a battery of memory tasks. We mined the
84 dataset for potential associations between memory, mental health, and exercise.

85 **Experiment**

86 **Participants**

87 We recruited experimental participants by posting our experiment as a Human Intelligence Task
88 (HIT) on the Amazon Mechanical Turk platform. We limited participation to Mechanical Turk
89 Workers who had been assigned a "Masters" designation on the platform, given to workers who
90 score highly across several metrics on a large number of HITs, according to a proprietary algorithm

91 managed by Amazon. We further limited our participant pool to participants who self-reported that
92 they were fluent in English and regularly used a Fitbit fitness tracker device. A total of 160 workers
93 accepted our HIT in order to participate in our experiment. Of these, we excluded all participants
94 who failed to log into their Fitbit account (giving us access to their anonymized fitness tracking
95 data), encountered technical issues (e.g., by accessing the HIT using an incompatible browser,
96 device, or operating system), or who ended their participation prematurely, before completing the
97 full study. In all, 113 participants remained that contributed usable data to the study.

98 For their participation, workers received a base payment of \$5 per hour (computed in 15
99 minute increments, rounded up to the nearest 15 minutes), plus an additional performance-based
100 bonus of up to \$5. Our recruitment procedure and study protocol were approved by Dartmouth's
101 Committee for the Protection of Human Subjects.

102 **Gender, age, and race.** Of the 113 participants who contributed usable data, 77 reported their
103 gender as female, 35 as male, and 1 chose not to report their gender. Participants ranged in age
104 from 19–68 years old (25th percentile: 28.25 years; 50th percentile: 32 years; 75th percentile: 38
105 years). Participants reported their race as White (90 participants), Black or African American (11
106 participants), Asian (7 participants), Other (4 participants), and American Indian or Alaska Native
107 (3 participants). One participant opted not to report their race.

108 **Languages.** All participants reported that they were fluent in either 1 and 2 languages (25th
109 percentile: 1; 50th percentile: 1; 75th percentile: 1), and that they were “familiar” with between 1
110 and 11 languages (25th percentile: 1; 50th percentile: 2; 75th percentile: 3).

111 **Reported medical conditions and medications.** Participants reported having and/or taking med-
112 ications pertaining to the following medical conditions: anxiety or depression (4 participants),
113 recent head injury (2 participants), high blood pressure (1 participant), bipolar (1 participant),
114 hypothyroidism (1 participant), and other unspecified medications (1 participant). Participants
115 reported their current and typical stress levels on a Likert scale as very relaxed (-2), a little relaxed
116 (-1), neutral (0), a little stressed (1), or very stressed (2). The “current” stress level reflected par-

117 ticipants' stress at the time they participated in the experiment. Their responses ranged from -2
118 to 2 (current stress: 25th percentile: -2; 50th percentile: -1; 75th percentile: 1; typical stress: 25th
119 percentile: 0; 50th percentile: 1; 75th percentile: 1). Participants also reported their current level of
120 alertness on a Likert scale as very sluggish (-2), a little sluggish (-1), neutral (0), a little alert (1),
121 or very alert (2). Their responses ranged from -2 to 2 (25th percentile: 0; 50th percentile: 1; 75th
122 percentile: 2). Nearly all (111 out of 113) participants reported that they had normal color vision,
123 and 15 participants reported uncorrected visual impairments (including dyslexia and uncorrected
124 near- or far-sightedness).

125 **Residence and level of education.** Participants reported their residence as being located in the
126 suburbs (36 participants), a large city (30 participants), a small city (23 participants), rural (14 partic-
127 ipants), or a small town (10 participants). Participants reported their level of education as follows:
128 College graduate (42 participants), Master's degree (23 participants), Some college (21 partici-
129 pants), High school graduate (9 participants), Associate's degree (8 participants), Other graduate
130 or professional school (5 participants), Some graduate training (3 participants), or Doctorate (2
131 participants).

132 **Reported water and coffee intake.** Participants reported the number of cups of water and coffee
133 they had consumed prior to accepting the HIT. Water consumption ranged from 0–6 cups (25th
134 percentile: 1; 50th percentile: 3; 75th percentile: 4). Coffee consumption ranged from 0–4 cups (25th
135 percentile: 0; 50th percentile: 1; 75th percentile: 2).

136 **Tasks**

137 Upon accepting the HIT posted on Mechanical Turk, the worker was directed to read and fill out
138 a screening and consent form, and to share access to their anonymized Fitbit data via their Fitbit
139 account. After consenting to participate and successfully sharing their Fitbit data, participants
140 filled out a survey and then engaged in a series of memory tasks (Fig. 1). All stimuli and code for
141 running the full Mechanical Turk experiment may be found [here](#).

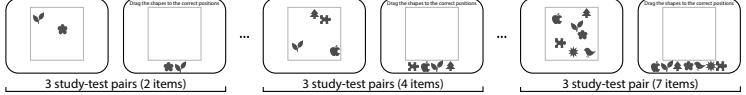
		Main task and immediate memory test		Delayed memory test
a.	Free recall	1  Study words GRIDDLE PICKLE SAUCER ... CARPET <small>16 words per list</small> <small>4 lists</small>	Memory test <small>Please type each word you remember into the prompt:</small> <input type="text"/>	5  <small>Please type each word you remember into the prompt:</small> <input type="text"/>
b.	Naturalistic recall	2  Watch a short video (The Temple of Knowledge)  <small>Video clip plays</small>	Memory tests <small>Please type anything you remember about what happened in the video you watched:</small> <input type="text"/>	6  <small>Please type anything you remember about what happened in the video you watched:</small> <input type="text"/>
c.	Foreign language flashcards	3  Study flashcards the boy BUACHAILL the milk BAINNE the bread ARÁN ... the water UISCE <small>10 English-Gaelic pairs</small>	Memory test  <small>Multiple choice</small>	7  <small>Multiple choice</small>
d.	Spatial learning	4  Memorize the positions of increasing numbers of shapes <small>3 study-test pairs (2 items)</small> ... <small>3 study-test pairs (4 items)</small> ... <small>3 study-test pair (7 items)</small>		N/A

Figure 1: Battery of memory tasks. **a. Free recall.** Participants study 16 words (presented one at a time), followed by an immediate memory test where they type each word they remember from the just-studied list. In the delayed memory test, participants type any words they remember studying, from any list. **b. Naturalistic recall.** Participants watch a brief video, followed by two immediate memory tests. The first test asks participants to write out what happened in the video. The second test has participants answer a series of multiple choice questions about the conceptual content of the video. In the delayed memory test, participants (again) write out what happened in the video. **c. Foreign language flashcards.** Participants study a sequence of 10 English-Gaelic word pairs, each presented with an illustration of the given word. During an immediate memory test, participants perform a multiple choice test where they select the Gaelic word that corresponds to the given photograph. During the delayed memory test, participants perform a second multiple choice test, where they select the Gaelic word that corresponds to each of a new set of photographs. **d. Spatial learning.** In each trial, participants study a set of randomly positioned shapes. Next, the shapes' positions are altered, and participants are asked to drag the shapes back to their previous positions. **All panels.** The gray numbers denote the order in which participants experienced each task or test.

¹⁴² **Survey questions.** We collected the following demographic information from each participant:
¹⁴³ their birth year, gender, highest (academic) degree achieved, race, language fluency, and language
¹⁴⁴ familiarity. We also collected information about participants' health and wellness, including about
¹⁴⁵ their vision, alertness, stress, sleep, coffee and water consumption, location of their residence,
¹⁴⁶ activity typically required for their job, and exercise habits.

¹⁴⁷ **Free recall (Fig. 1a).** Participants studied a sequence of four word lists, each comprising 16 words.
¹⁴⁸ After studying each list, participants received an immediate memory test, whereby they were asked
¹⁴⁹ to type (one word at a time) any words they remembered from the just-studied list, in any order.

¹⁵⁰ Words were presented for 2 s each, in black text on a white background, followed by a 2 s blank
¹⁵¹ (white) screen. After the final 2 s pause, participants were given 90 s to type in as many words
¹⁵² as they could remember, in any order. The memory test was constructed such that the participant
¹⁵³ could only see the text of the current word they were typing; when they pressed any non-letter
¹⁵⁴ key, the current word was submitted and the text box they were typing in was cleared. This was
¹⁵⁵ intended to prevent participants from retroactively editing their previous responses.

¹⁵⁶ The word lists participants studied were drawn from the categorized lists reported in Ziman
¹⁵⁷ et al. (2018). Each participant was assigned four unique randomly chosen lists (in a randomized
¹⁵⁸ order), selected from a full set of 16 lists. Each chosen list was then randomly shuffled before
¹⁵⁹ presenting the words to the participants.

¹⁶⁰ Participants also performed a final delayed memory test where they were given 180 s to type
¹⁶¹ out any words they remembered from *any* of the 4 lists they had studied.

¹⁶² Recalled words within an edit distance of 2 (i.e., a Levenshtein Distance less than or equal to
¹⁶³ 2) of any word in the wordpool were "autocorrected" to their nearest match. We also manually
¹⁶⁴ corrected clear typos or misspellings by hand (e.g., we corrected "hippoptumas" to "hippopota-
¹⁶⁵ mus", "zucinni" to "zucchini", and so on). Finally, we lemmatized each submitted word to match
¹⁶⁶ the plurality of the matching wordpool word (e.g., "bongo" was corrected to "bongos", and so
¹⁶⁷ on). After applying these corrections, any submitted words that matched words presented on the
¹⁶⁸ just-studied list were tagged as "correct" recalls, and any non-matching words were discarded

¹⁶⁹ as “errors.” Because participants were not allowed to edit the text they entered, we chose not to
¹⁷⁰ analyze these putative “errors,” since we could not distinguish typos from true misrememberings.

¹⁷¹ **Naturalistic recall (Fig. 1b).** Participants watched a 2.5 minute video clip entitled “The Temple
¹⁷² of Knowledge.” The video comprises an animated story told to StoryCorps by Ronald Clark, who
¹⁷³ was interviewed by his daughter, Jamilah Clark. The narrator (Ronald) discusses growing up
¹⁷⁴ living in an apartment over Washington Heights branch of the New York Public Library, where his
¹⁷⁵ father worked as a custodian during the 1940s.

¹⁷⁶ After watching the video clip, participants were asked to type out anything they remembered
¹⁷⁷ about what happened in the video. They typed their responses into a text box, one sentence at a
¹⁷⁸ time. When the participant pressed the return key or typed any final punctuation mark (“.”, “!”, or
¹⁷⁹ “?”) the text currently entered into the box was “submitted” and added to their transcript, and the
¹⁸⁰ text box was cleared to prevent further editing of any already-submitted text. This was intended to
¹⁸¹ prevent participants from retroactively editing their previous responses. Participants were given
¹⁸² up to 10 minutes to enter their responses. After 4 minutes participants were given the option of
¹⁸³ ending the response period early, e.g., if they felt they had finished entering all of the information
¹⁸⁴ they remembered. Each participant’s transcript was constructed from their submitted responses by
¹⁸⁵ combining the sentences into a single document and removing extraneous whitespace characters.

¹⁸⁶ Following this 4–10 minute free response period, participants were given a series of 10 multiple
¹⁸⁷ choice questions about the conceptual content of the story. All participants received the same
¹⁸⁸ questions, in the same order.

¹⁸⁹ Participants also performed a final delayed memory test, where they carried out the free
¹⁹⁰ response recall task a second time, near the end of the testing session. This resulted in a second
¹⁹¹ transcript, for each participant.

¹⁹² **Foreign language flashcards (Fig. 1c).** Participants studied a series of 10 English-Gaelic word
¹⁹³ pairs in a randomized order. We selected the Gaelic language both for its relatively small number of
¹⁹⁴ native speakers and for its dissimilarity to other commonly spoken languages amongst Mechanical

¹⁹⁵ Turk Workers. We verified (via self report) that all of our participants were fluent in English and
¹⁹⁶ that they were neither fluent nor familiar with Gaelic.

¹⁹⁷ Each word's "flashcard" comprised a cartoon depicting the given word, the English word or
¹⁹⁸ phrase in lowercase text (e.g., "the boy"), and the Gaelic word or phrase in uppercase text (e.g.,
¹⁹⁹ "BUACHAIL"). Each flashcard was displayed for 4 s, followed by a 3 s interval (during which
²⁰⁰ the screen was cleared) prior to the next flashcard presentation.

²⁰¹ After studying all 10 flashcards, participants were given a multiple choice memory test where
²⁰² they were shown a series of novel photographs, each depicting one of the 10 words they had
²⁰³ learned. They were asked to select which (of 4 unique options) Gaelic word went with the given
²⁰⁴ picture. The 3 incorrect options were selected at random (with replacement across trials), and the
²⁰⁵ order in which the choices appeared to the participant were also randomized. Each of the 10 words
²⁰⁶ they had learned were tested exactly once.

²⁰⁷ Participants also performed a final delayed memory test, where they were given a second set of
²⁰⁸ 10 questions (again, one per word they had studied). For this second set of questions participants
²⁰⁹ were prompted with a new set of novel photographs, and new randomly chosen incorrect choices
²¹⁰ for each question. Each of the 10 original words they had learned were (again) tested exactly once
²¹¹ during this final memory test.

²¹² **Spatial learning (Fig. 1d).**

²¹³ **Fitness tracking using Fitbit devices**

²¹⁴ **Processing Fitbit data**

²¹⁵ **Raw metrics.**

²¹⁶ **Comparing recent versus baseline measurements.**

²¹⁷ **Exploratory correlation analyses**

²¹⁸ **Imputation and interpolation of missing data.**

²¹⁹ **Regression-based prediction analyses**

²²⁰ **Reverse correlation analyses**

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²²⁸ **Data and code availability**

²²⁹ All analysis code and data used in the present manuscript may be found [here](#).

²³⁰ **Author contributions**

²³¹ Concept: J.R.M. Experiment implementation and data collection: G.M.N. Analyses: G.M.N., E.C.,
²³² P.C.F., and J.R.M. Writing: J.R.M.

²³³ **Competing interests**

²³⁴ The authors declare no competing interests.

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²³⁷ high-impact exercise. *Osteoporosis International*, 4:72–75.

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